Attosecond control of relativistic electron nanobunches using two colour fields

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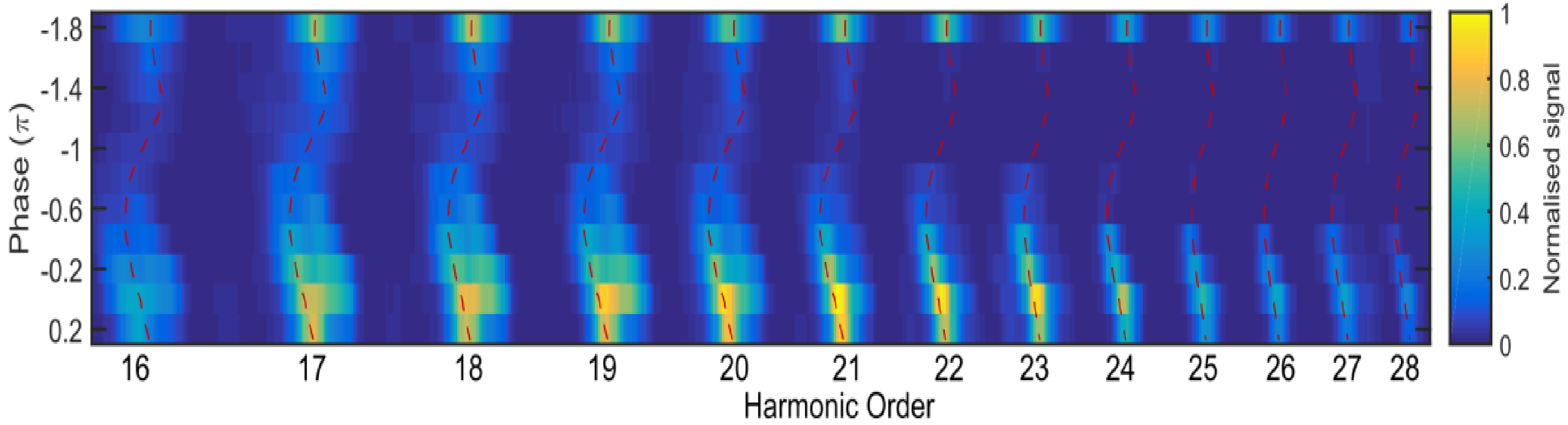

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Acknowledgements

Queen‘s University Belfast:

- Mark Yeung
- Steven Cousens
- Mark Coughlan
- Li Lu

Friedrich-Schiller-Universität Jena

- S. Rykovanov,
- J. Bierbach,
- E. Eckner,
- S. Kuschel,
- A. Woldegeorgis,
- A. Sävert,
- G. G. Paulus

- C. Rodel

Outline

- Surface high harmonic generation (SHHG) mechanisms (**brief overview**)
    - Coherent Wake Emission
    - Relativistically Oscillating Mirrors
- The role of plasma scale length and experimental control
- Coherent synchrotron emission (CSE) and dense nanobunches of electrons
- Two colour interactions – attosecond control of bunch formation
    - Concept
    - Methods
    - Results
- Outlook

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HHG from bulk relativistic plasma medium

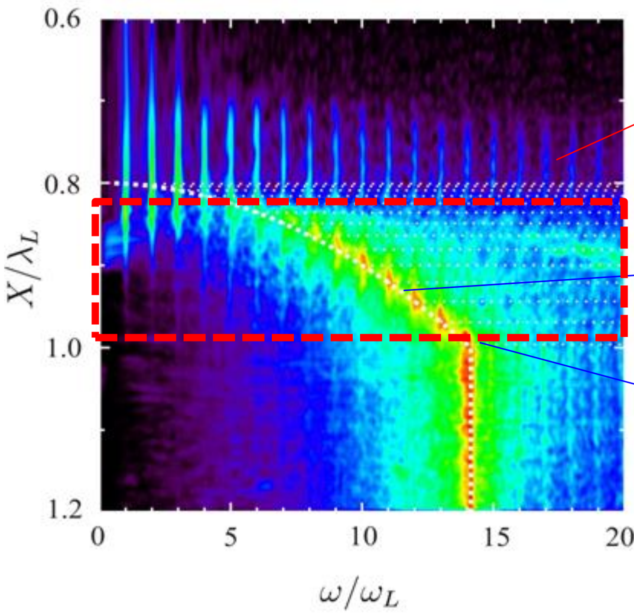
Coherent XUV generation has been studied primarily reflection from relativistic plasmas

2 mechanisms studied analytically/numerically and observed experimentally

- *Coherent Wake Emission -CWE* (**F. Quéré et al.,** *PRL* **96, 125004, 2006)**
- *Relativistically Oscillating Mirror – ROM* (**T. Baeva et al.,** PRE, **74, 046404 2008)**

PIC Simulation

Distance



Harmonic order

Also: emission at N_{crit} surface: – extends to much higher orders **Relativistically Oscillating Mirror**

Emission from within bulk plasma

Emission only extends up to maximum plasma frequency ω_{pmax}

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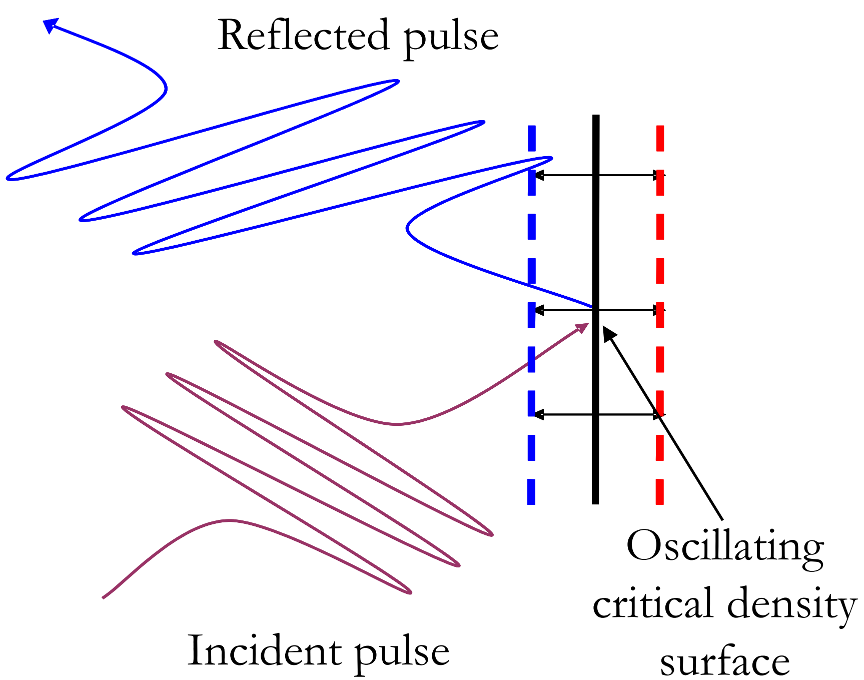
Relativistically oscillating plasmas

- The target surface is highly ionised by the leading edge of the pulse – becomes rapidly over dense (reflecting to incident radiation)
- The collective electron motion created by the incident electromagnetic wave can be considered as an oscillating mirror



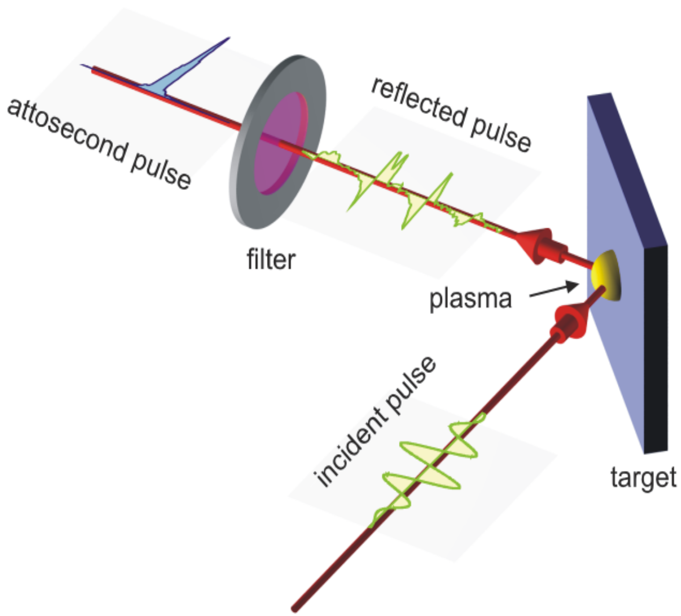


Illustration from George Tsakiris
New Journal Physics 8, 19, 2006

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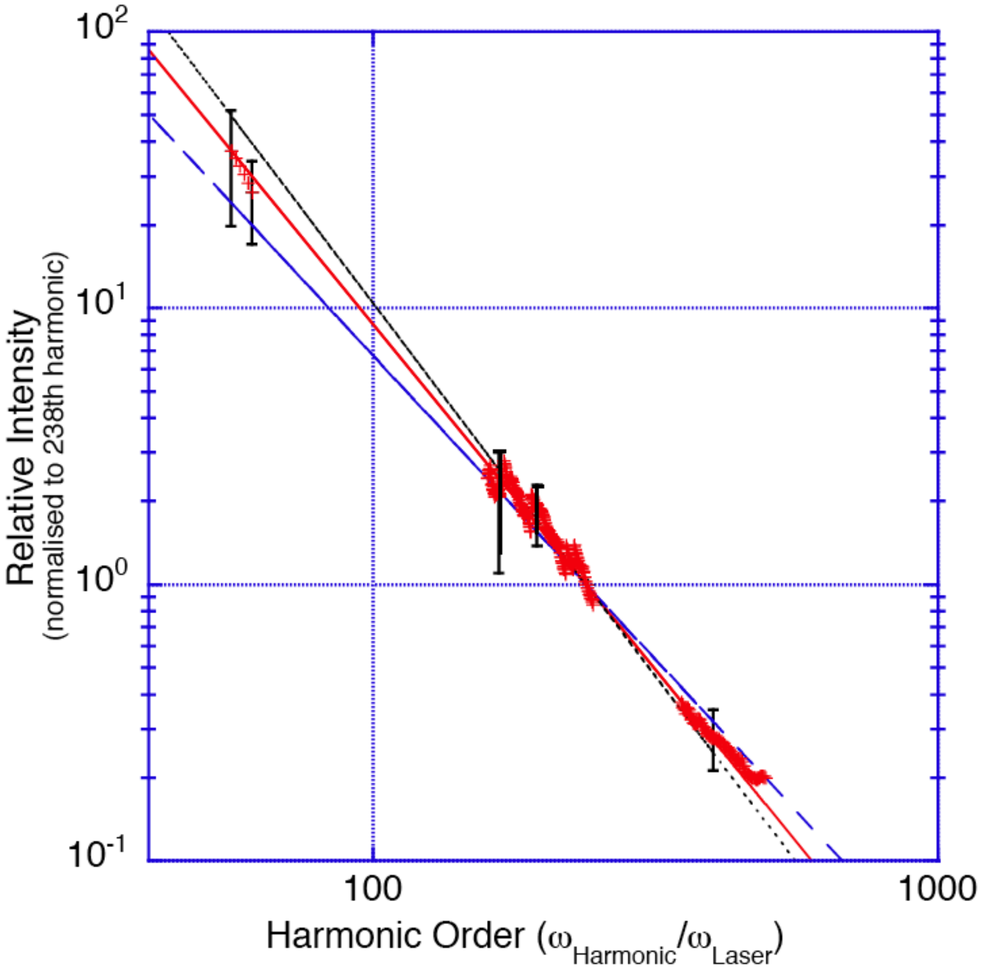
Experimental verification of ROM



Experimental data from Vulcan PW shows ROM scaling

$I(n) = n^{-2.5\pm.2}$

for a=10

Intensity $>10^{20}$ Wcm^{-2}

Pulse duration 500fs (FWHM)

B. Dromey *et al*, **Nature Physics, 2**, 456-459 **(2006)**

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ROM Properties and keV Harmonics

- Attosecond structure

Y. Nomura et al, **Nature Physics, 5, 124 - 128 (2009)**

- Radiation is beamed and can have low divergence

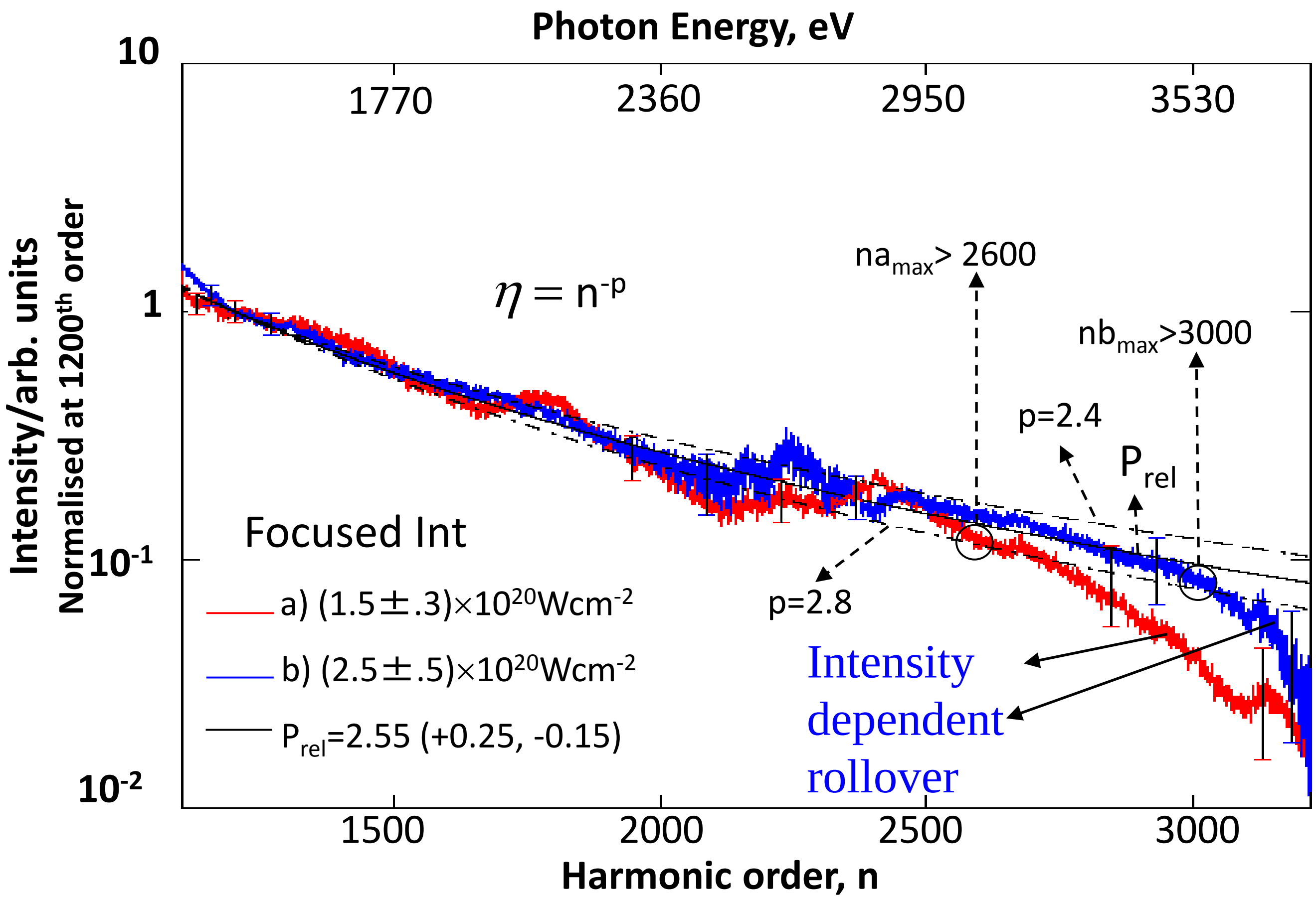
***B. Dromey** et al*, **Nature Physics, 5, 146 - 152 (2009)**

- Max Frequency $\sim 8^{1/2}\gamma^3\omega_0$

- keV photon energies have been observed

Problem: Conversion efficiency does not match that expected from theory

keV ROM harmonics and the efficiency roll-over



B. Dromey *et al*., ***Phys*. Rev. Lett. 99, 085001 (2007)**

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Density ramp requirements

Coherent XUV Emission in reflection from relativistic plasmas

Flat, well defined surface

Flatness

Smooth reflected phase fronts

=> High spatial quality

Well defined

No extended generation region

=> High conversion efficiency

Harmonic efficiency depends strongly on plasma scale length, L

$L/\lambda \approx 0.01$ to ~1, where λ is the driving laser wavelength

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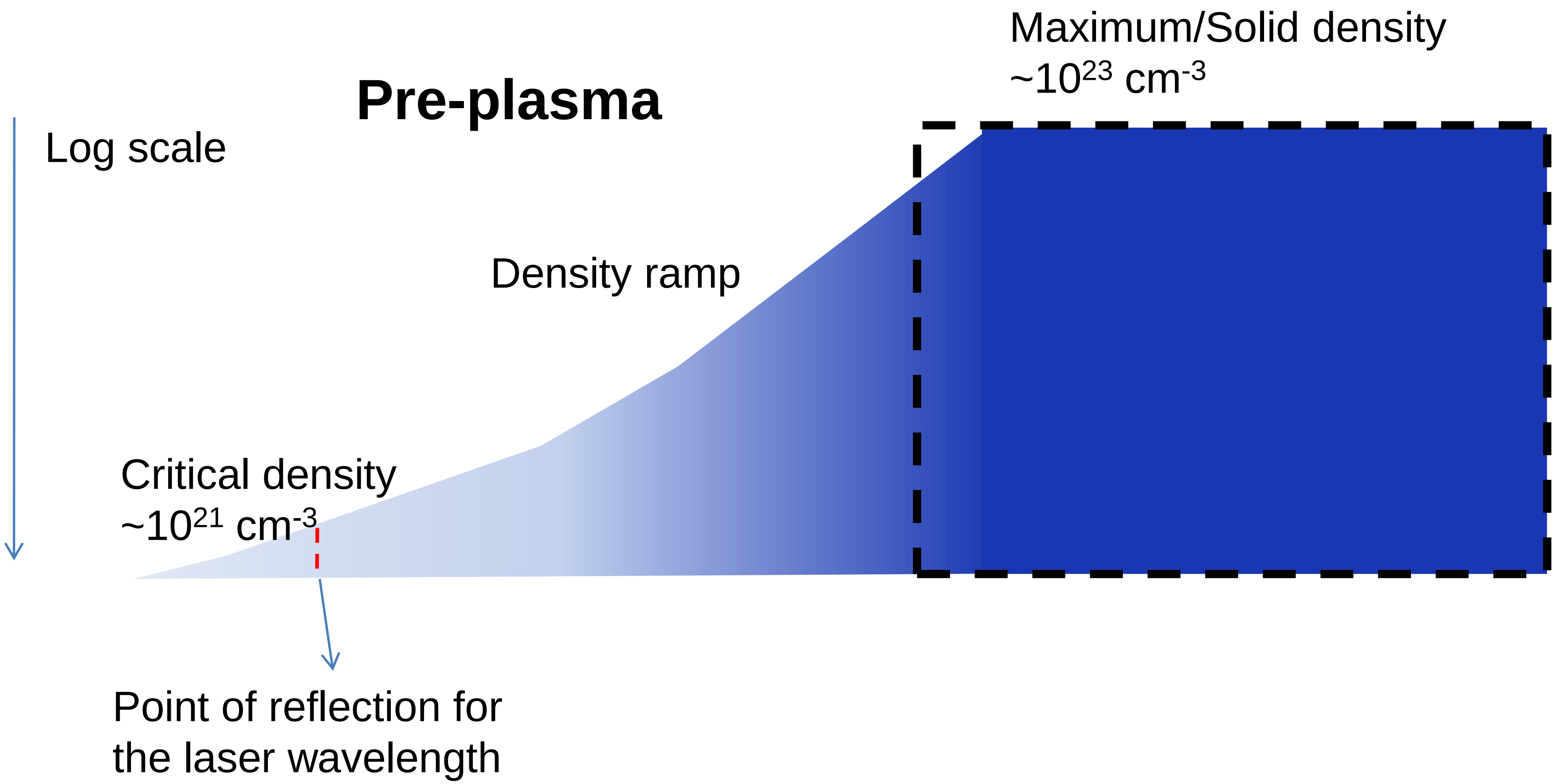
The relativistic plasma medium - schematic



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Experiment on JETI-40 laser

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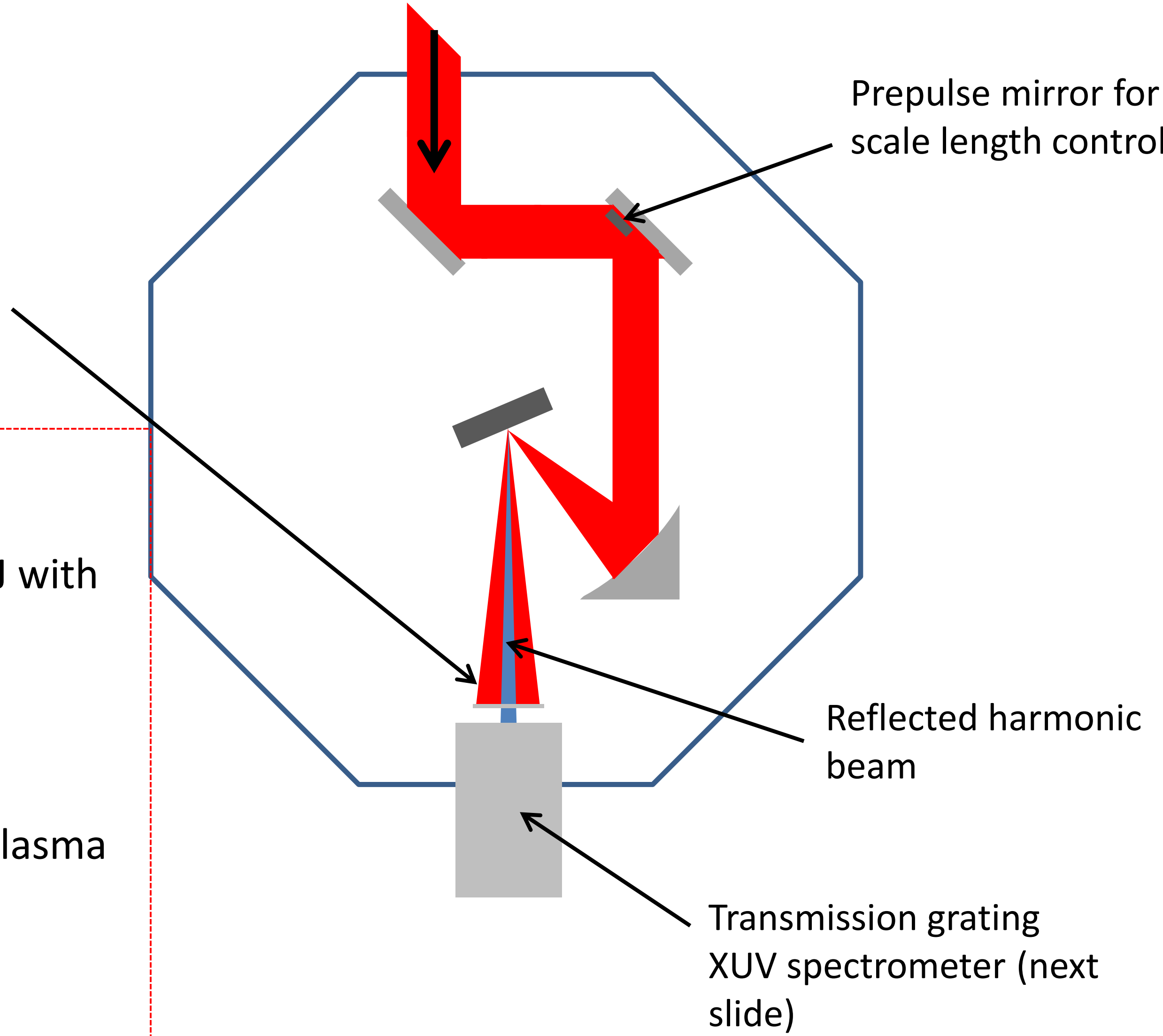

JETI - 40 system

- 800nm
- compressed pulses of ≈700mJ with ≈30fs duration
- Repetition rate of 10Hz
- Contrast enhancement by a plasma mirror system
- Using F-3 focusing we get an intensity of $\approx 2X10^{19} Wcm^{-2}$

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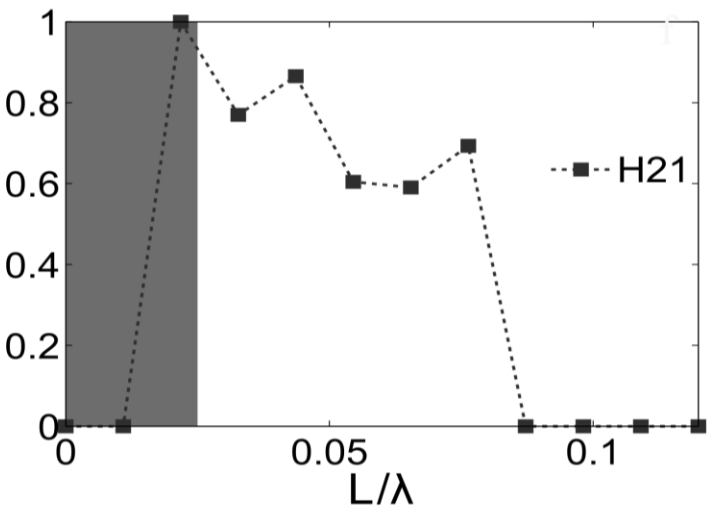
Role of plasma scale length

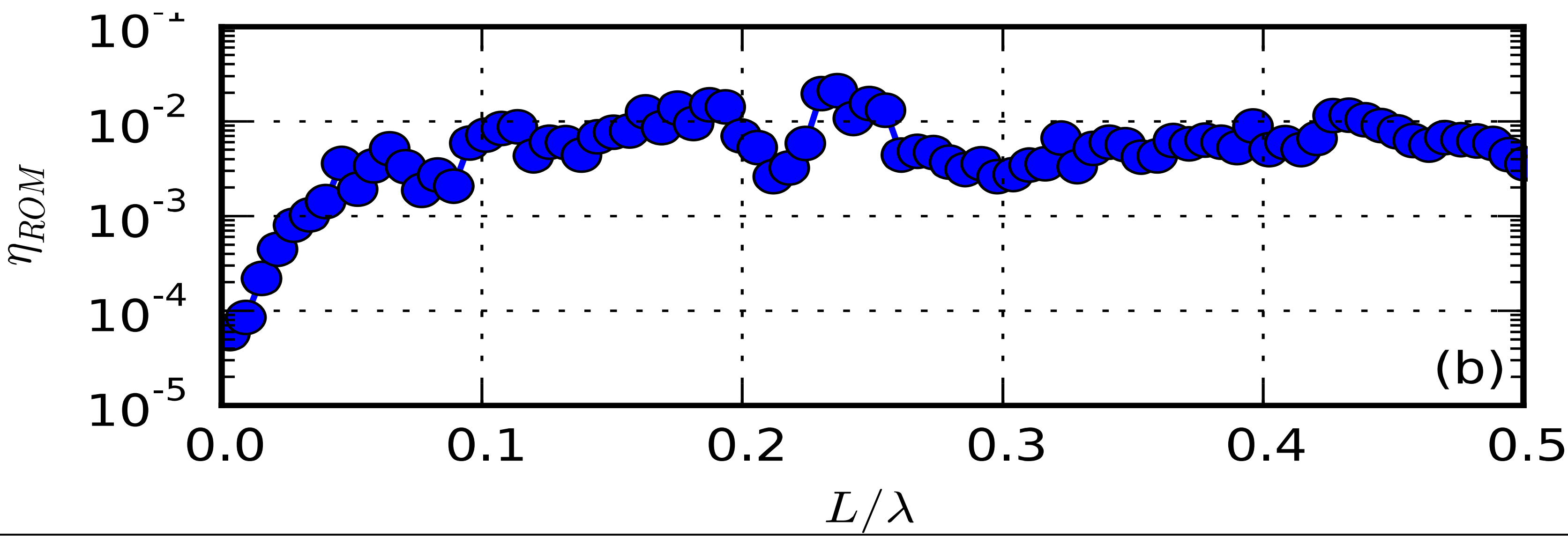


1D PIC predicts broad optimum Beyond 0.1 L/ λ l.

Experiment peaks at ~0.025 L/λ

⇒ Possible to optimise harmonic efficiency via scale length

S. Kahaly et al, PRL, 110, 175001, 2013



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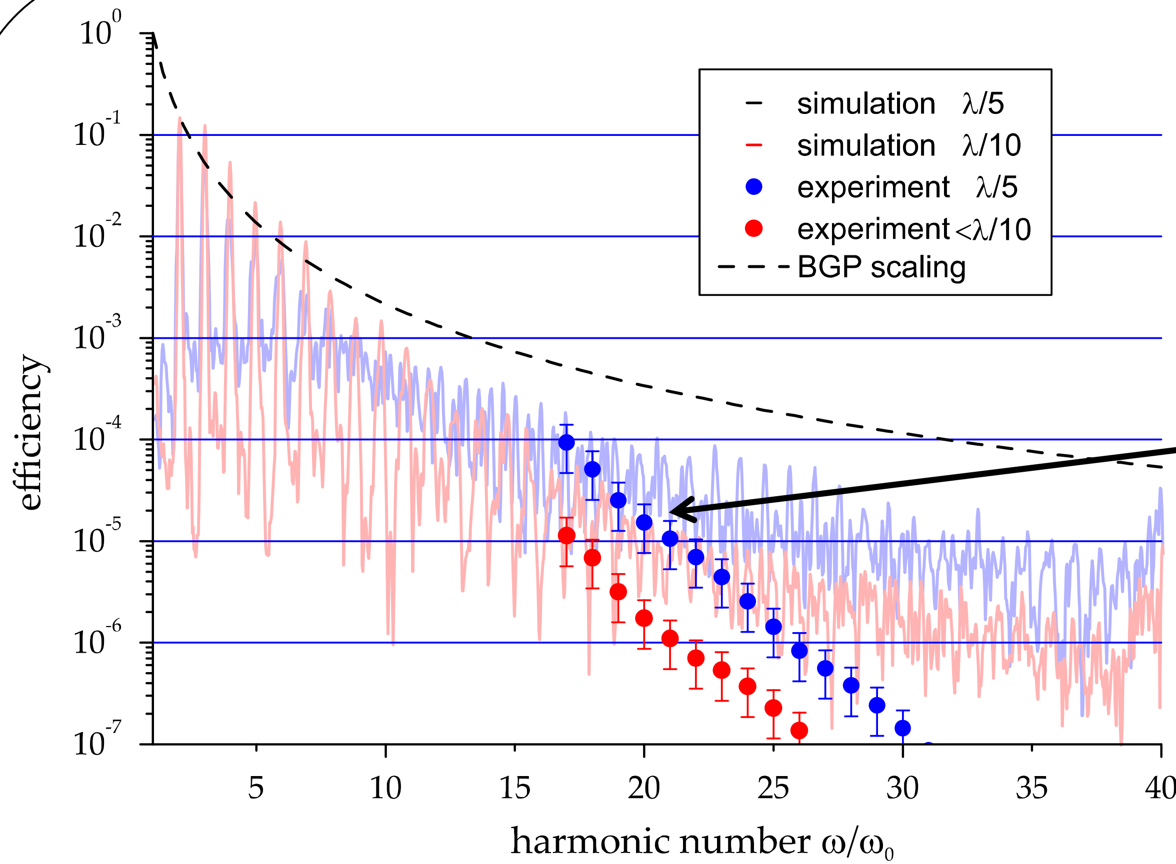
Problem for short pulse interactions



Expected scaling not achieved, although much better conversion efficiency

C. Rödel et al. PRL 109, 125002, 2012

Origin of discrepancy not fully clear:

- shape of density profile?
- Transverse surface waves?

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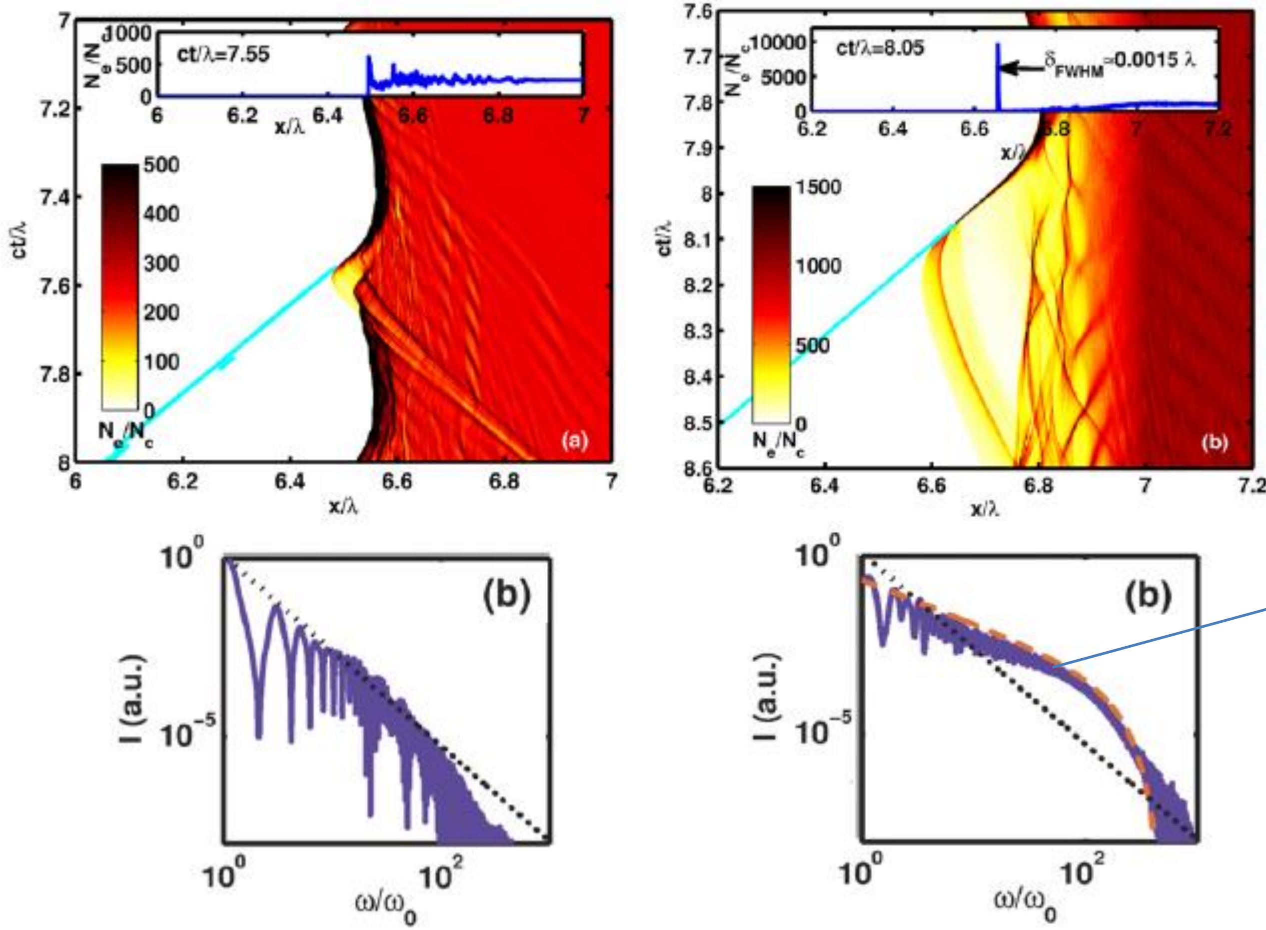
Coherent Synchrotron Emission - CSE



Shallower than $I_n \propto n^{-8/3}$, steeper cut off

Dense nanobunches of electrons can be driven to emitted coherently

Pukhov, A., *et al.*, **Plasma Phys. Control. Fusion 52** 124039 **(2010)**

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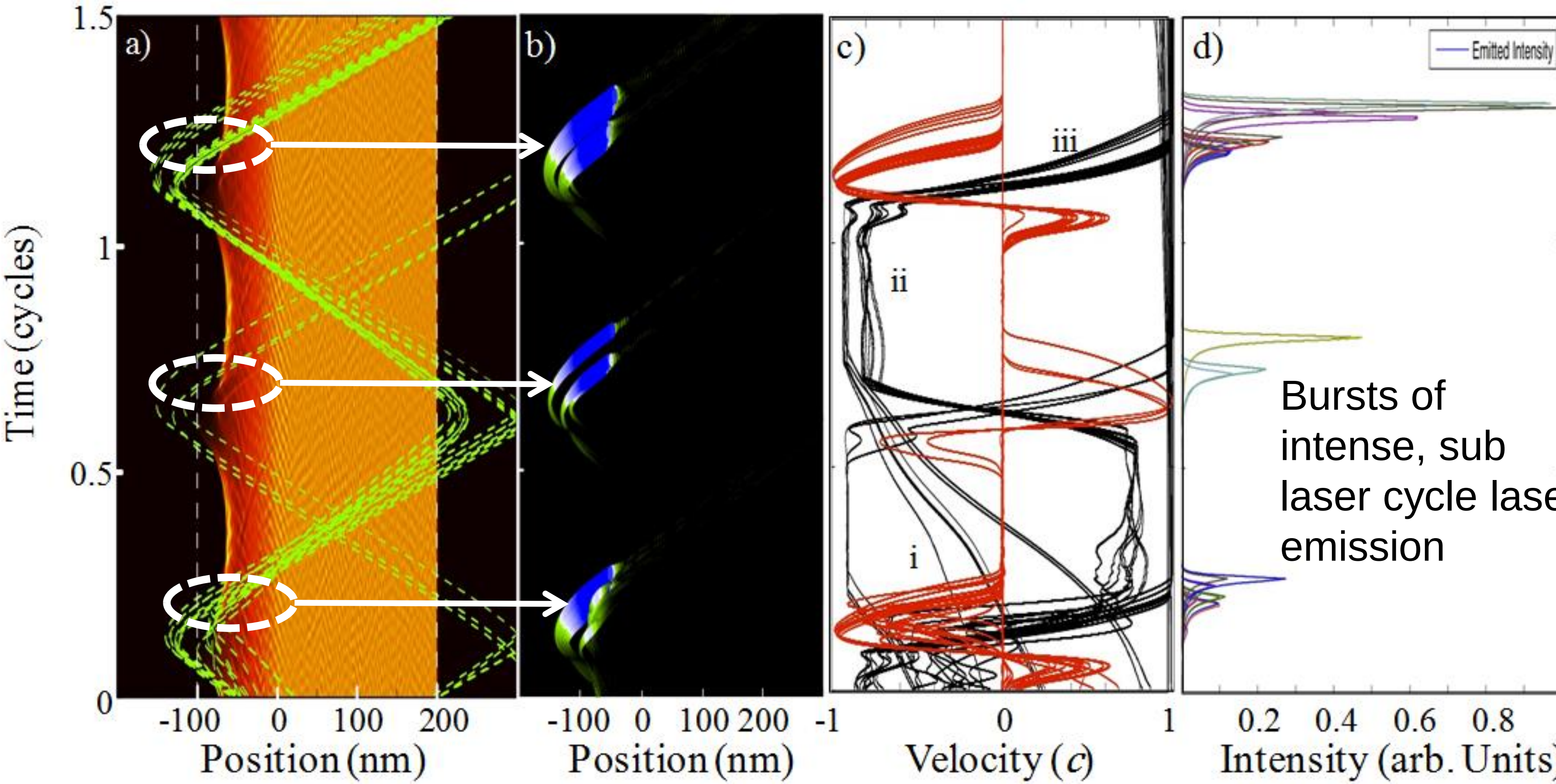
CSE (in transmission)

Overview of the mechanism

A few cycle super Gaussian pulse, normal incidence on a 200nm thick solid density ($800N_c$)



Bursts of intense, sub laser cycle laser emission

Dromey et al., **Nature Physics**, 8, 804 (2012)

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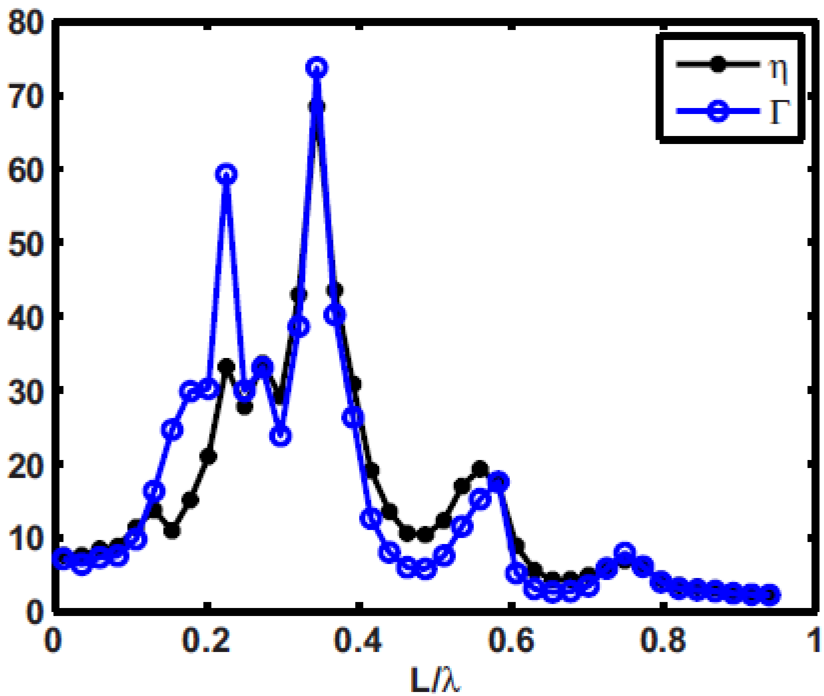
The role of plasma scalelength



For the coefficients = 1

ROM like spectra

For the coefficients >>1

CSE like spectra

An der Brugge, D., Pukhov, A., **Phys. Plasmas 17**, 033110 (2010)

Evolving plasma scale length conditions for multicycle pulses implies ROM-like spectra dominates

Is it possible to control bunch formation to enhance the emission of coherent XUV emission?

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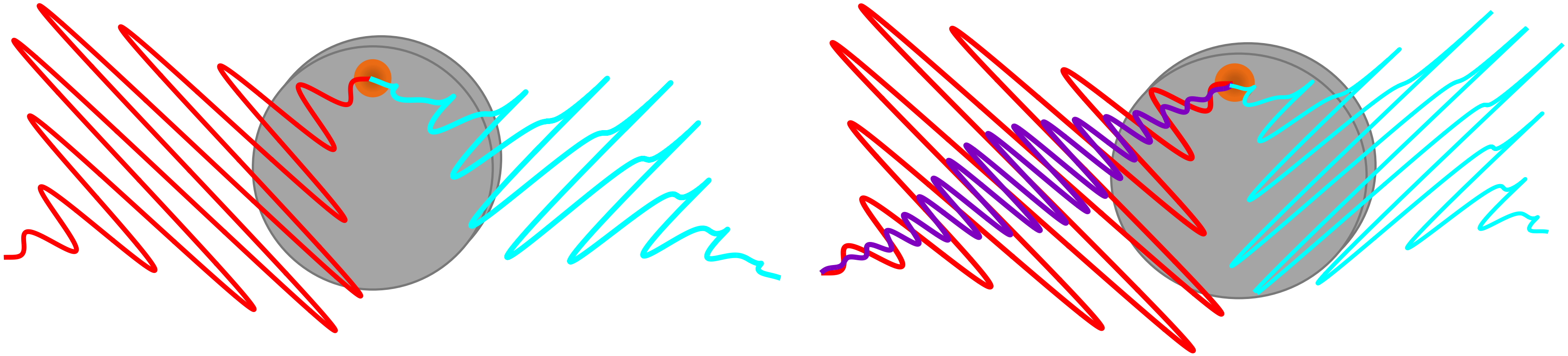
Two colour fields



- Fundamental driving field dressed with 2nd harmonic pulse
- Control over accelerating fields of surface bunches
  => optimisation of trajectories for XUV emission (high γ at right moment)
- Critical parameter is the relative phase of the 2nd harmonic field

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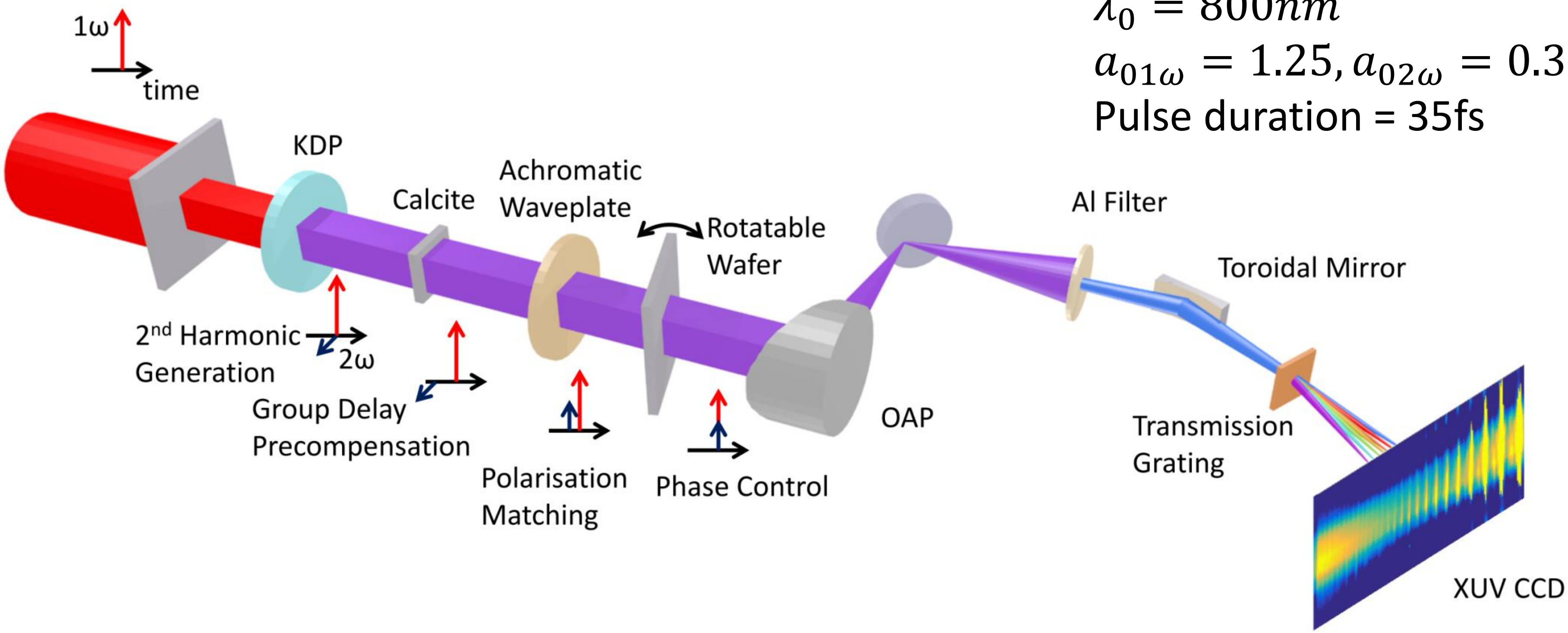
Experimental setup

JETI 40 Laser parameters:

$\lambda_0 = 800nm$

$a_{01\omega} = 1.25, a_{02\omega} = 0.35$

Pulse duration = 35fs



Attosecond phase control between fundamental laser pulse and second harmonic dressing field

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Substantial enhancement possible

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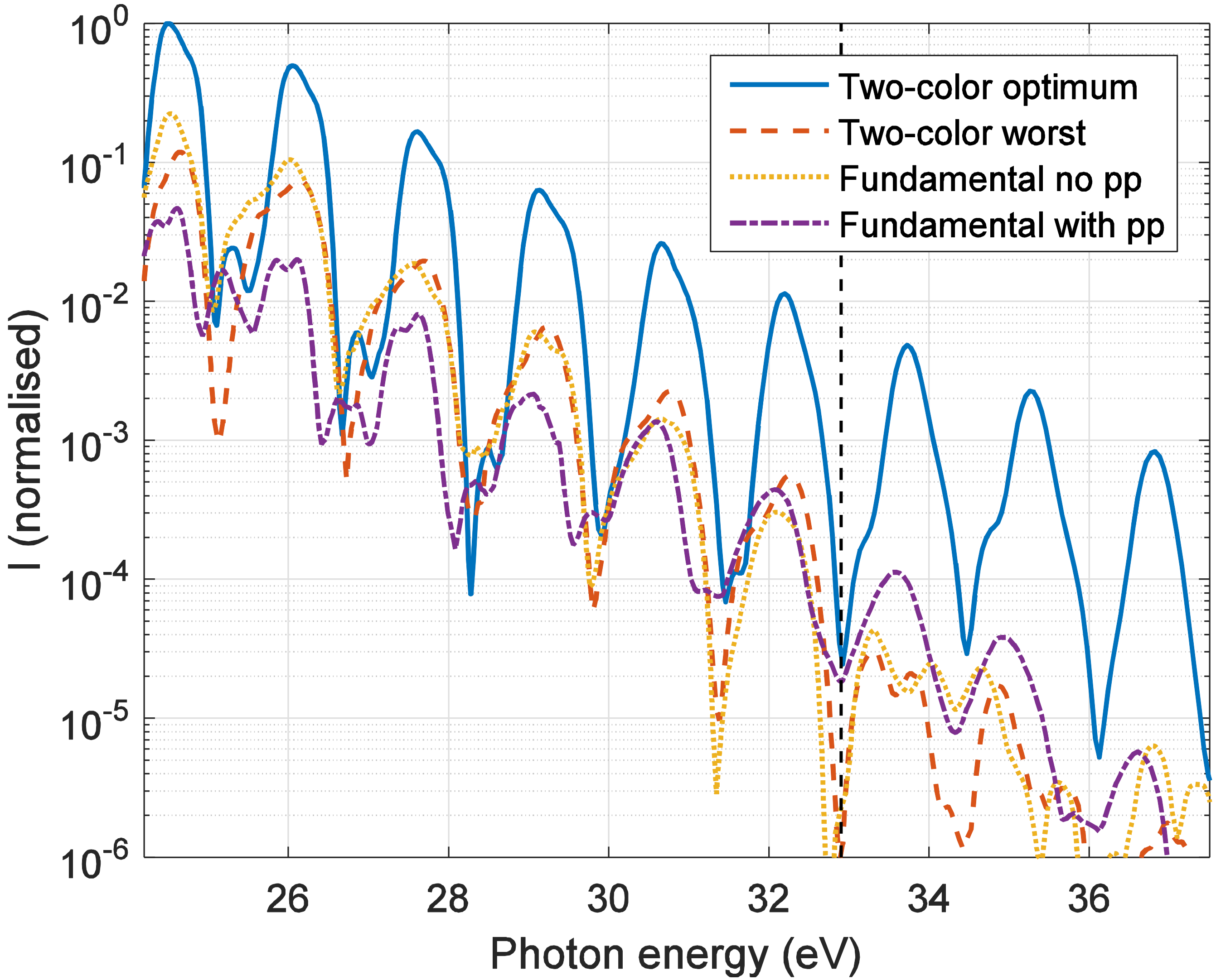
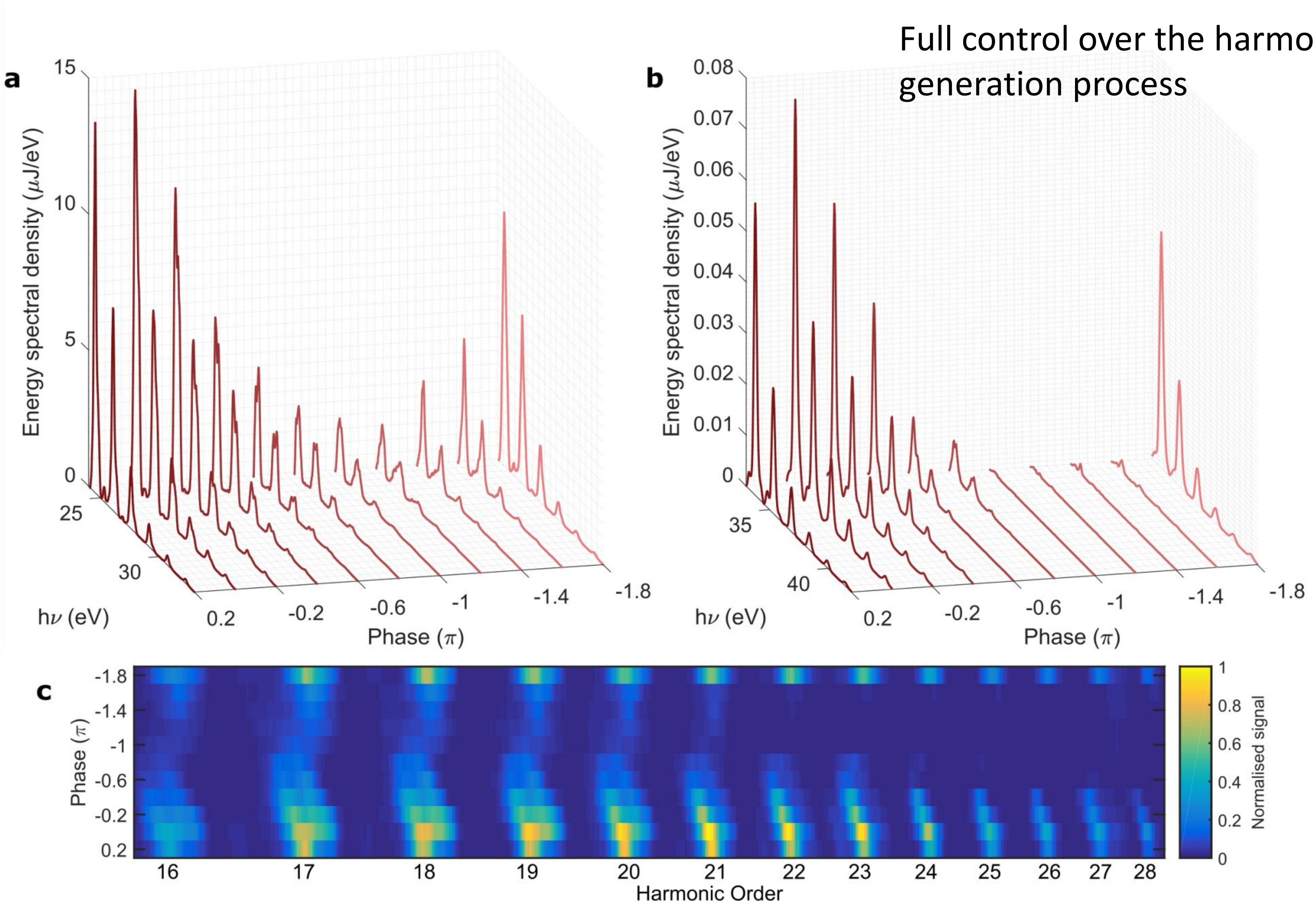


Total laser energy kept constant in all cases

M. Yeung et al., Nature Photonics **11**, 32–35 (2017)

Experimental results – tuneable enhancement

Full control over the harmonic generation process



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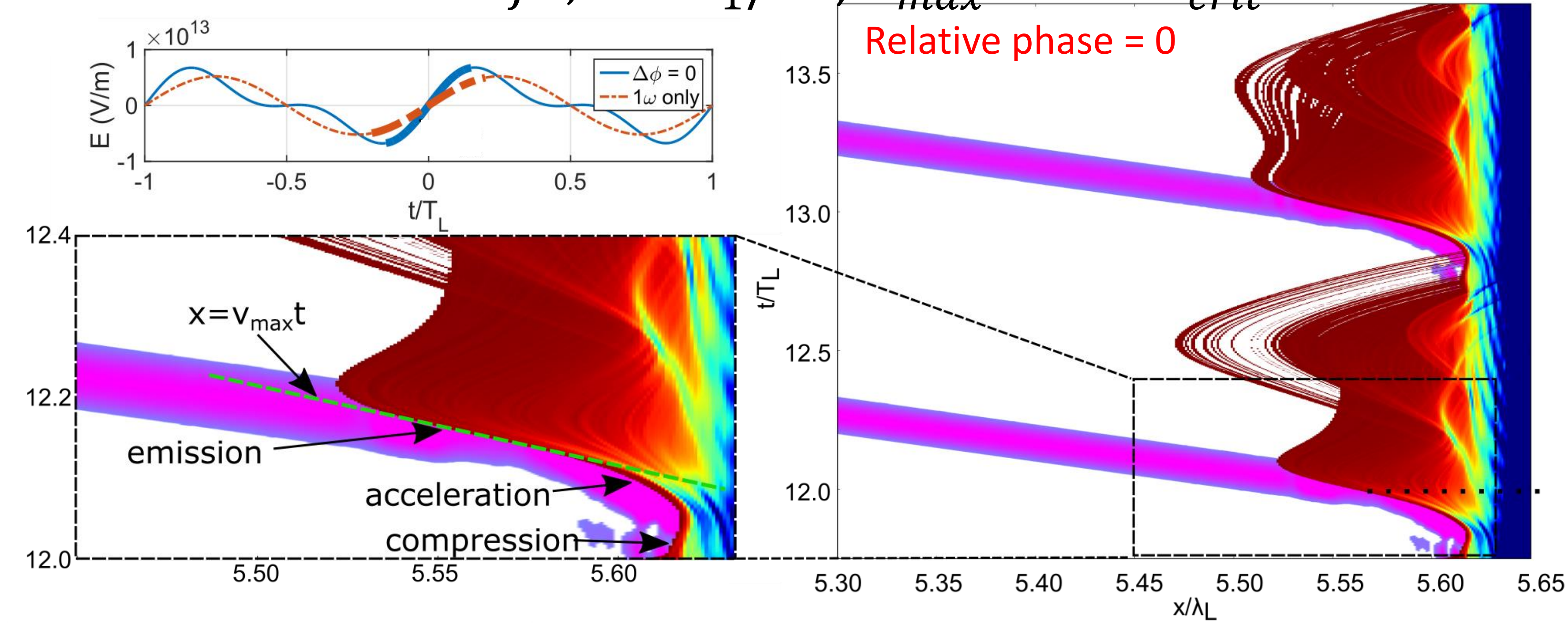
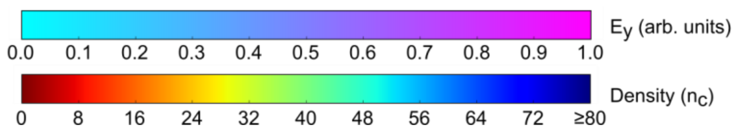
Two colour control of bunch formation - tuned

1D Particle-in-cell simulations: $\lambda_1 = 800nm, a_0 = 1.25, \lambda_2 = 400nm, a_0 = 0.35,$

Pulse duration $= 35fs, L = \lambda_1/40, n_{max} = 400n_{crit}$





Radiation filtered to contain frequencies >20th harmonic

Emitted radiation is bright and coherent

M. Yeung et al., Nature Photonics **11**, 32–35 (2017)

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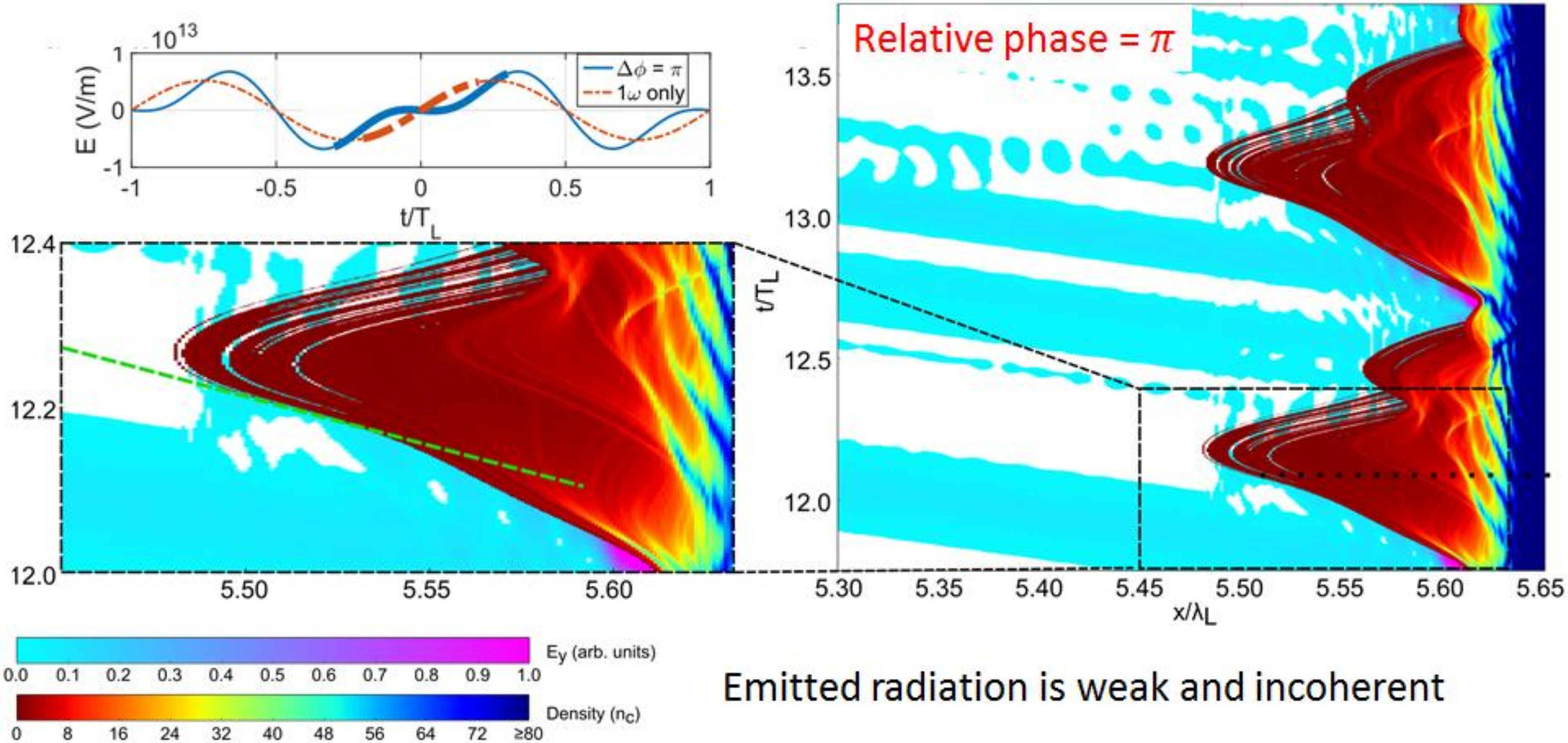
Two colour control of bunch formation - detuned

$\lambda_1 = 800nm, a_0 = 1.25, \lambda_2 = 400nm, a_0 = 0.35,$

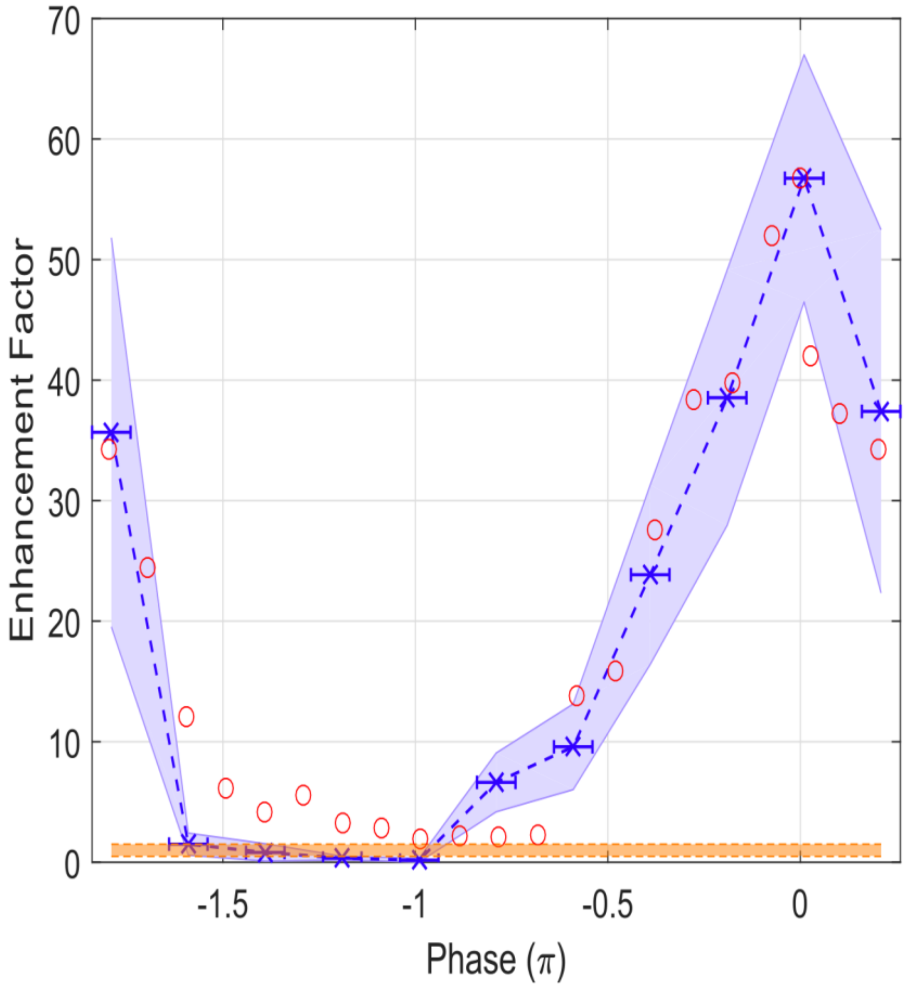
Pulse duration $= 35fs, L = \lambda_1/40, n_{max} = 400n_{crit}$



Emitted radiation is weak and incoherent

M. Yeung et al., Nature Photonics **11**, 32–35 (2017)

XUV Enhancement



Sum over 22nd to 27th harmonics

Observed enhancement from current experiment

$a_0 = 1.25$

M. Yeung et al., Nature Photonics **11**, 32–35 (2017)

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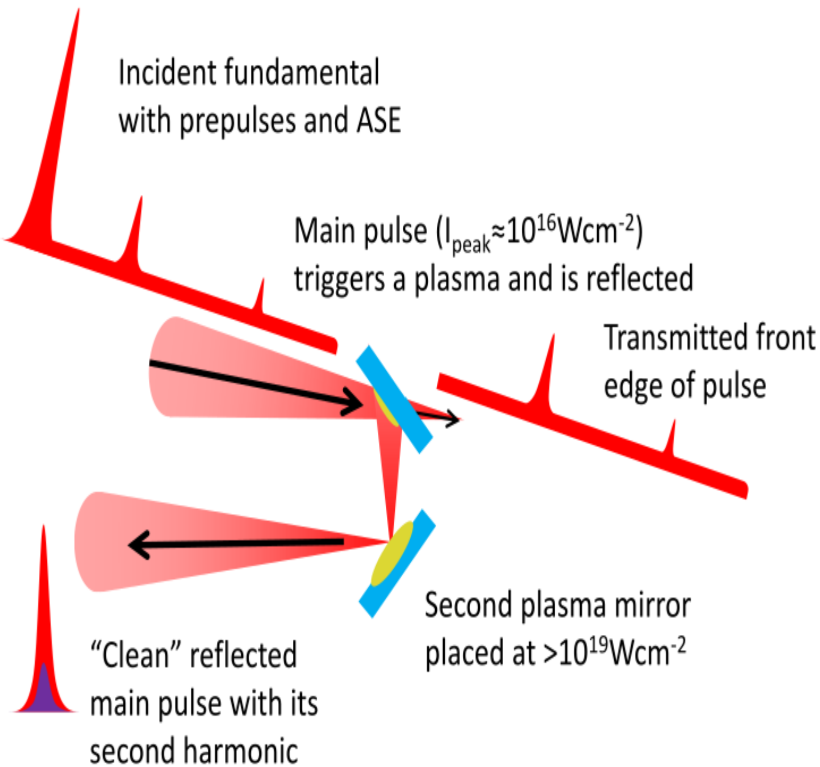
Outlook - Extension to PW class lasers



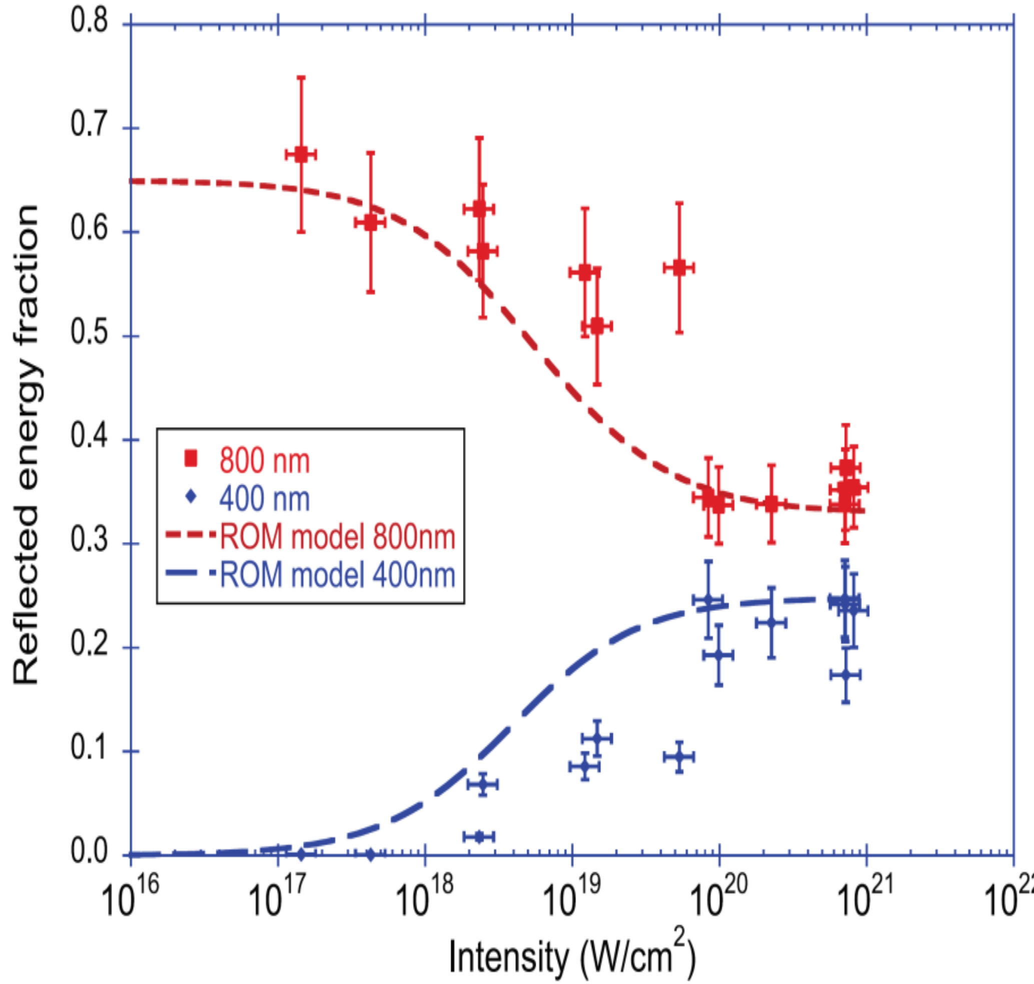


Figure from Streeter *et al.* New J. Phys. **13,** 023041 (2011)

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